CSC 252: Computer Organization Spring 2018: Lecture 9

Instructor: Yuhao Zhu

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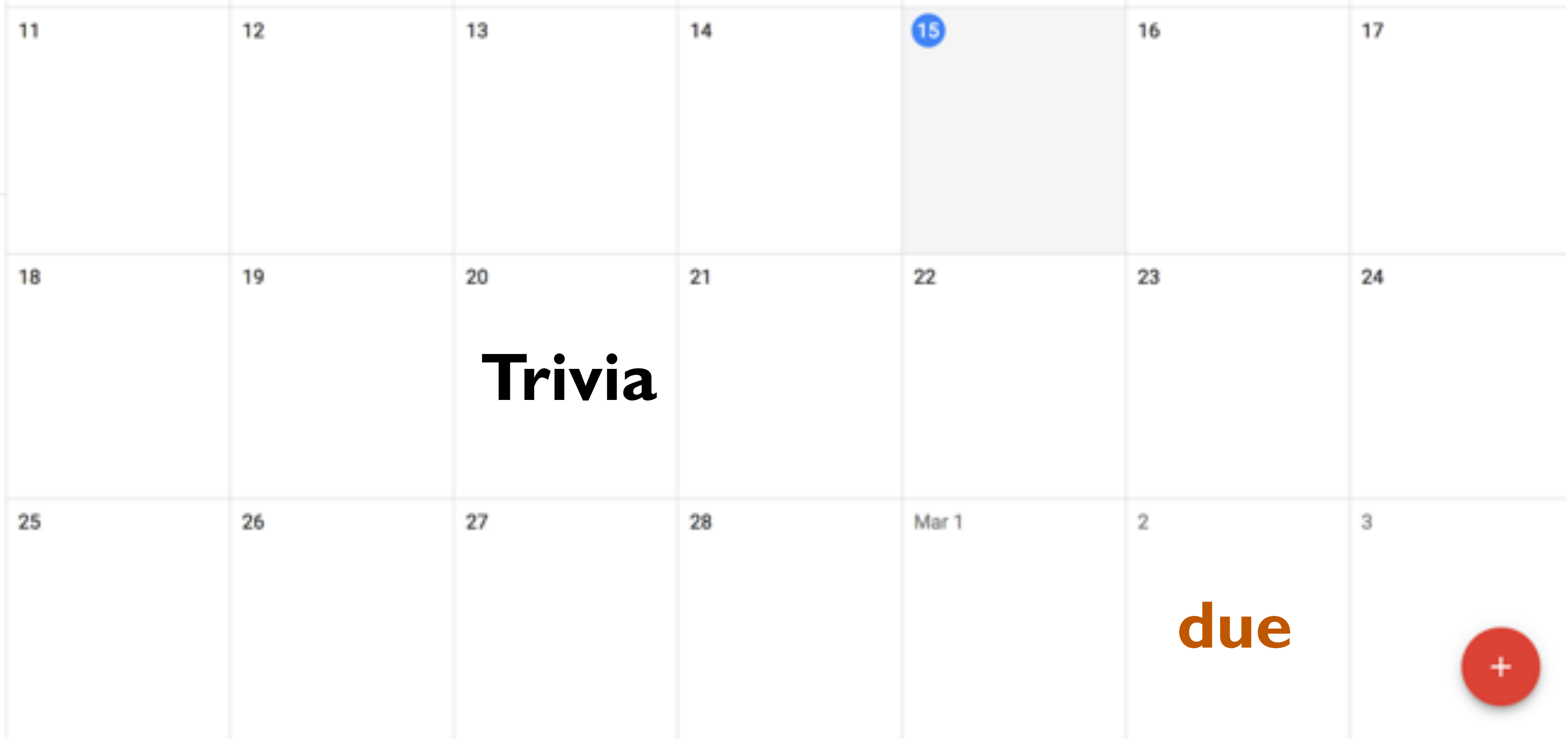
University of Rochester

Action Items:

- **Assignment 2 is due tomorrow, midnight**
- **Assignment 3 is out**

Announcement

- Programming Assignment 2 is due on this Friday, midnight
- Programming Assignment 3 is out
  - Trivia due on **Feb 20, noon**
  - Main assignment due on March 2, midnight



11	12	13	14	15	16	17
18	19	20 **Trivia**	21	22	23	24
25	26	27	28	Mar 1	2 **due**	3

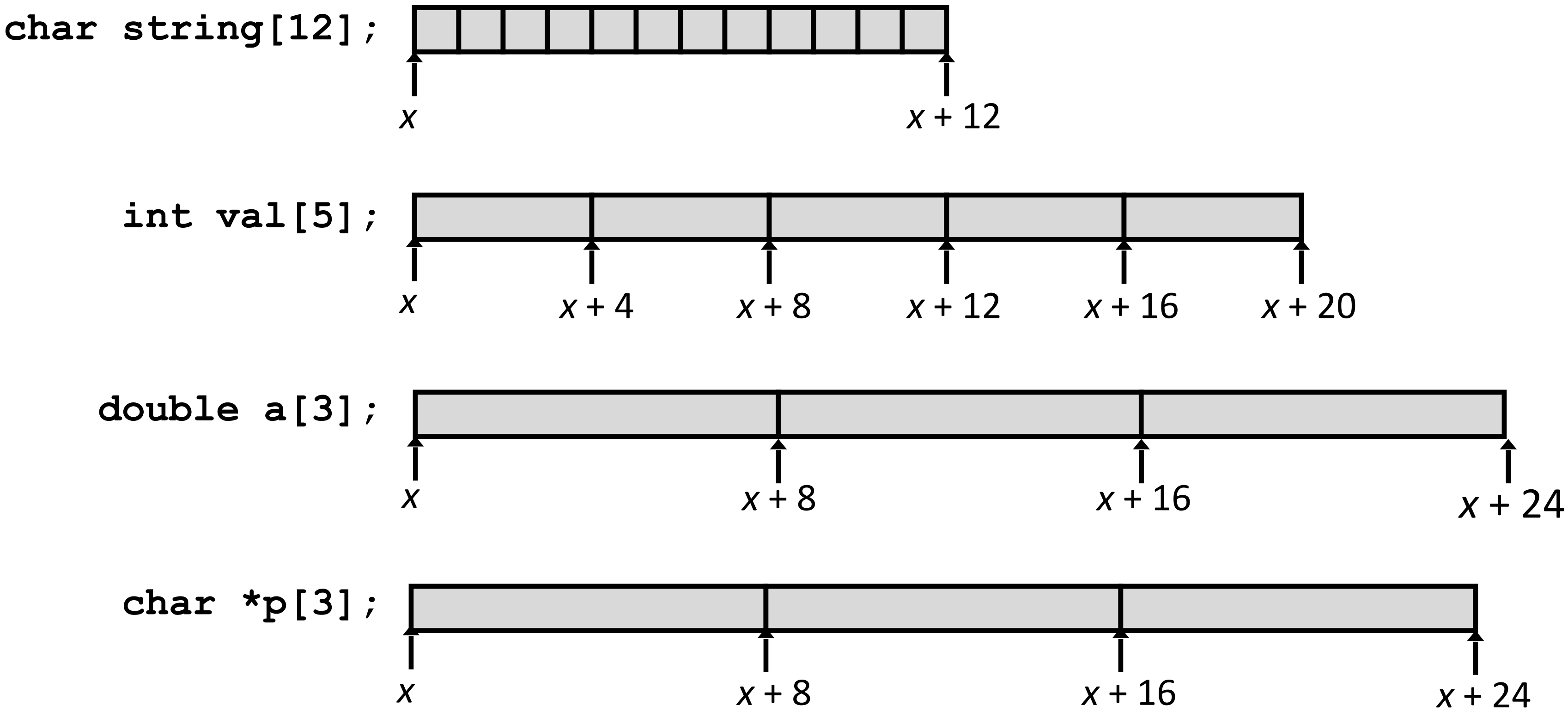
Today: Data Structures and Buffer Overflow

- Arrays
  - One-dimensional
  - Multi-dimensional (nested)
- Structures
  - Allocation
  - Access
  - Alignment
- Buffer Overflow

Array Allocation: Basic Principle

T **A[*L*];**

- Array of data type *T* and length *L*
- Contiguously allocated region of *L* * **sizeof**(*T*) bytes in memory



char string[12];

int val[5];

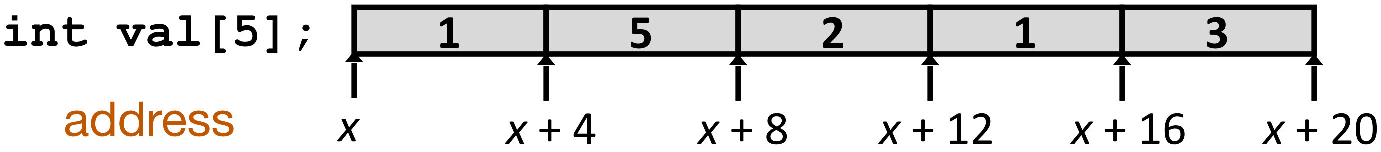
double a[3];

char *p[3];

Array Access: Basic Principle

T **A[*L*];**

- Array of data type *T* and length *L*
- Identifier **A** can be used as a pointer to array element 0: Type *T**



int val[5];

1 5 2 1 3

address

x *x* + 4 *x* + 8 *x* + 12 *x* + 16 *x* + 20

Reference	Type	Value
`val[4]`	`int`	3
`val`	`int *`	*x*
`val+1`	`int *`	*x* + 4
`&val[2]`	`int *`	*x* + 8
`val[5]`	`int`	??
`*(val+1)`	`int`	5
`val +` *i*	`int *`	*x* + 4 *i*

Multidimensional (Nested) Arrays

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- Declaration

  T **A**[*R*][*C*];

  - 2D array of data type *T*
  - *R* rows, *C* columns
  - Type *T* element requires *K* bytes

$$\begin{bmatrix} \mathtt{A[0][0]} & \cdots & \mathtt{A[0][C-1]} \\ \vdots & & \vdots \\ \mathtt{A[R-1][0]} & \cdots & \mathtt{A[R-1][C-1]} \end{bmatrix}$$

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- Array Size
  - *R* * *C* * *K* bytes

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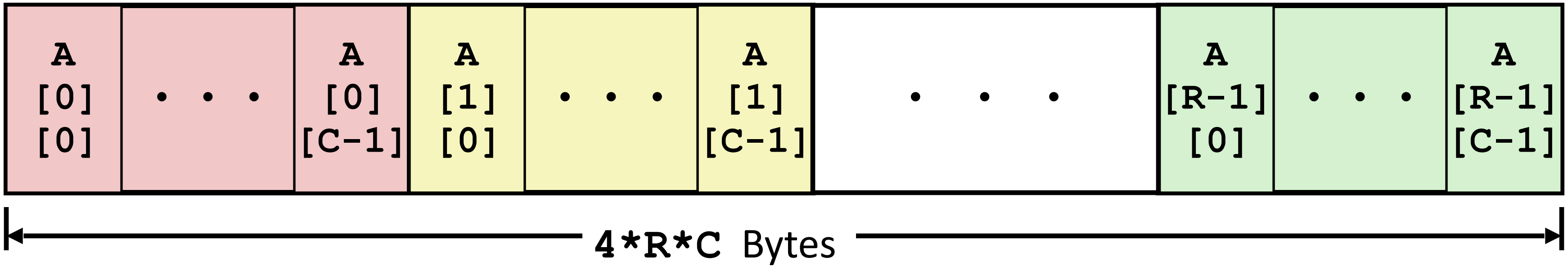
- Array Size
  - *R* * *C* * *K* bytes
- Arrangement
  - Row-Major Ordering in most languages, including C

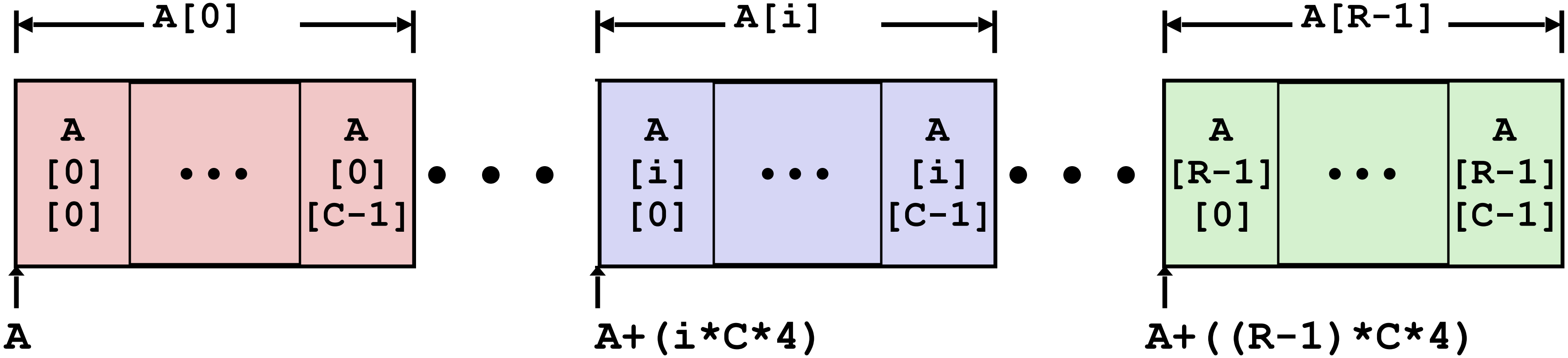
```
int A[R][C];
```



Nested Array Row Access

- T **`A`**[R][C];
    - **`A[i]`** is array of *C* elements
    - Each element of type T requires K bytes
    - Starting address A + i * (C * K)

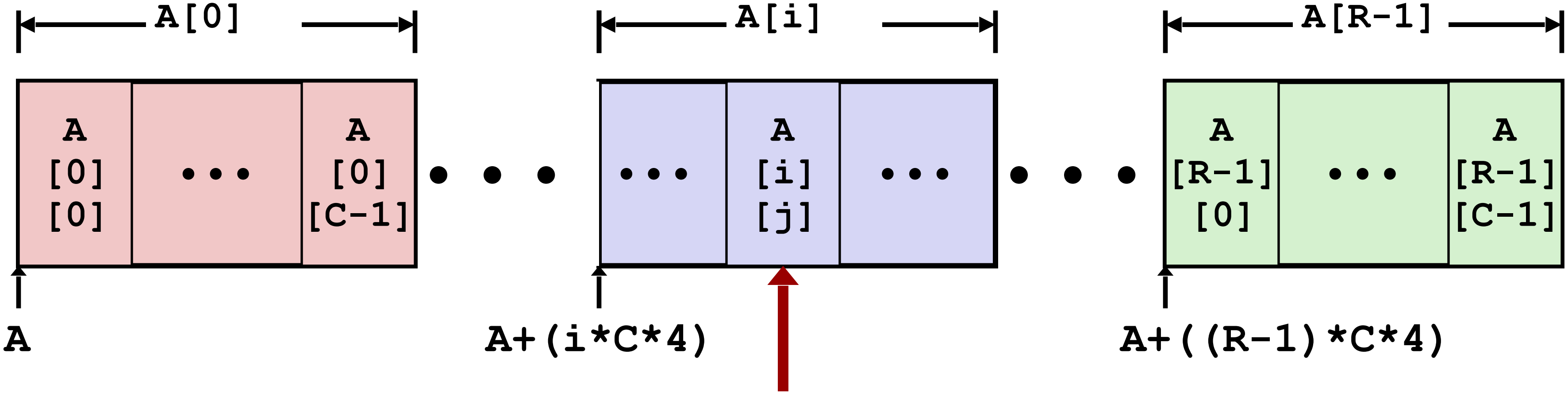
`int A[R][C];`



Nested Array Element Access

- Array Elements
  - **`A[i][j]`** is element of type *T*, which requires *K* bytes
  - Address **`A +`** *i* * (*C* * *K*) + *j* * *K* = *A* + (*i* * *C* + *j*)* *K*

```
int A[R][C];
```



A+(i*C*4)+(j*4)

Today: Data Structures and Buffer Overflow

- Arrays
  - One-dimensional
  - Multi-dimensional (nested)
- Structures
  - Allocation
  - Access
  - Alignment
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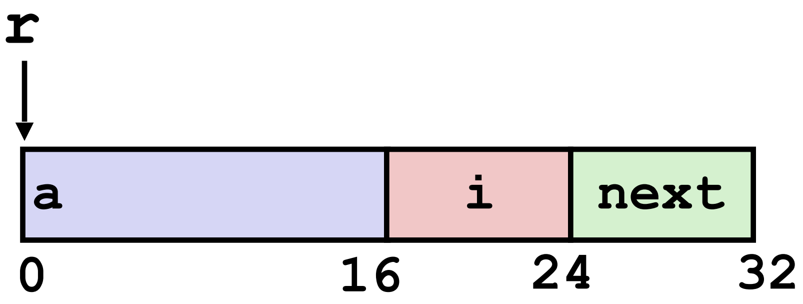
Structures

```
struct rec {
    int a[4];
    size_t i;
    struct rec *next;
};
```



- Characteristics
  - Contiguously-allocated region of memory
  - Refer to members within struct by names
  - Members may be of different types

Structures

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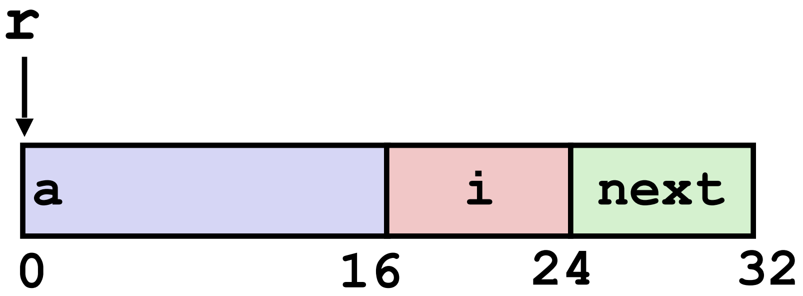

- Accessing struct member
  - Given a struct, we can use the `.` operator, just like in Java:
    - `struct rec r1; r1.i = val;`
  - What if we have a pointer to a struct: `struct rec* r = &r1`
    - Using `*` and `.` operators: `(*r).i = val;`
    - Or simply, the -> operator for short: `r->i = val;`

Generating Pointer to Structure Member

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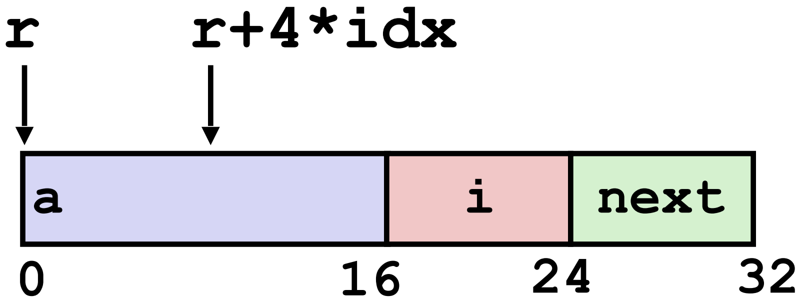

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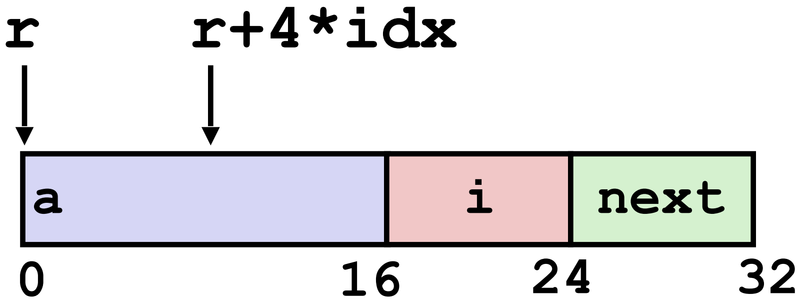

```
int *get_ap
 (struct rec *r, size_t idx)
{
  return &r->a[idx];
}
```

Generating Pointer to Structure Member

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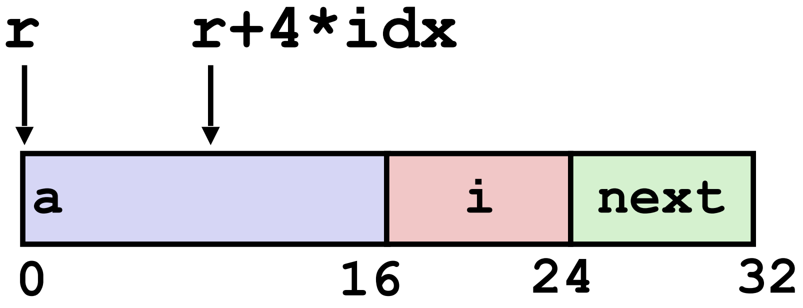

```
int *get_ap
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  return &r->a[idx];
}
```

```
&(r->a[idx])
```

```
&((*r).a[idx])
```

Generating Pointer to Structure Member

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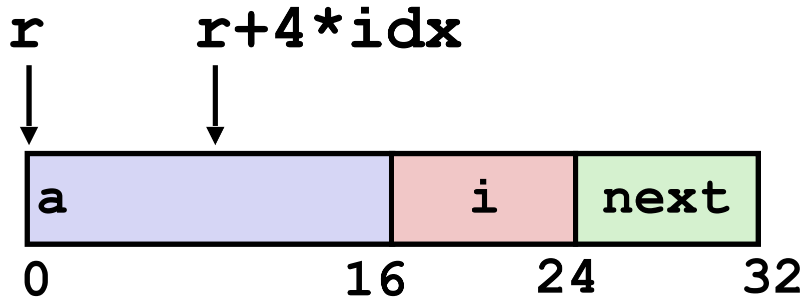

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{
  return &r->a[idx];
}
```

```
&(r->a[idx])
```

```
&((*r).a[idx])
```

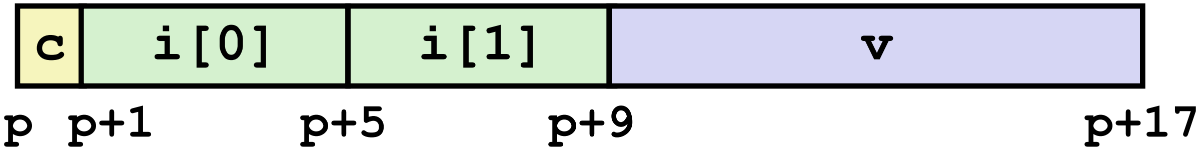
```
  # r in %rdi, idx in %rsi
  leaq  (%rdi,%rsi,4), %rax
  ret
```

Alignment

```
struct S1 {
  char c;
  int i[2];
  double v;
} *p;
```

Alignment

- Unaligned Data



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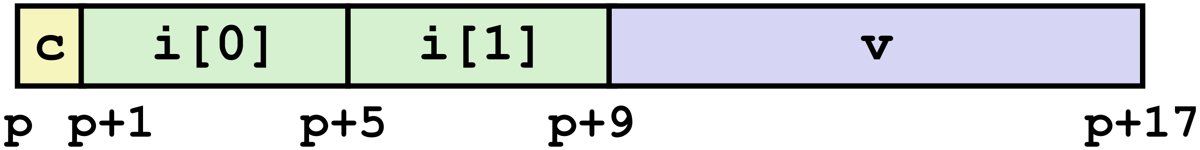

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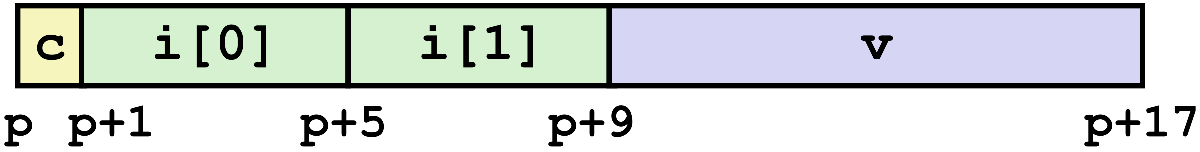

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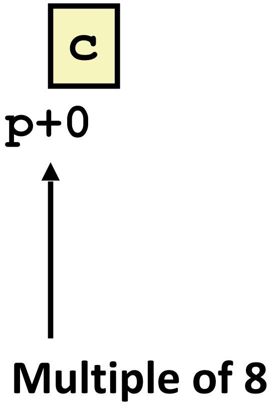

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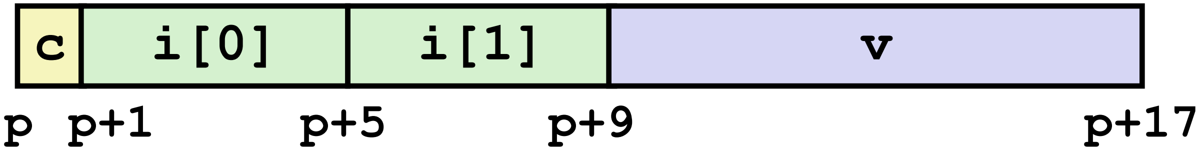
c i[0] i[1] v

p p+1 p+5 p+9 p+17

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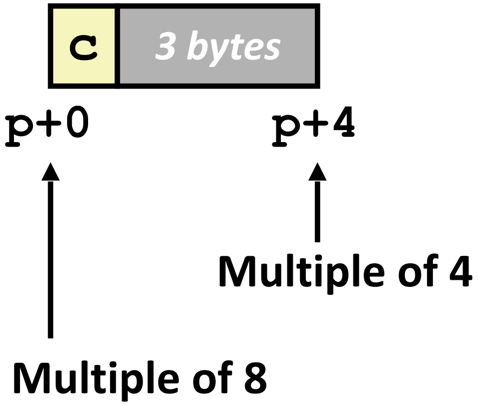
  - If the data type requires ***K*** bytes, address must be multiple of ***K***


c *3 bytes*

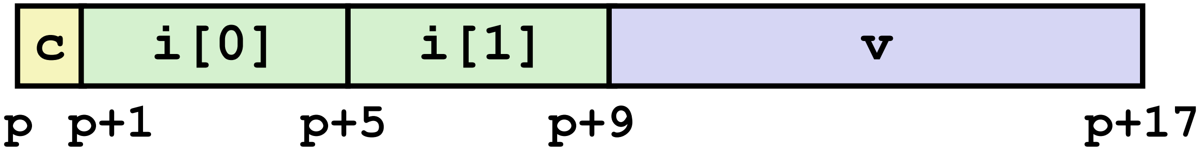
p+0 p+4

Multiple of 4

Multiple of 8

Alignment

- Unaligned Data



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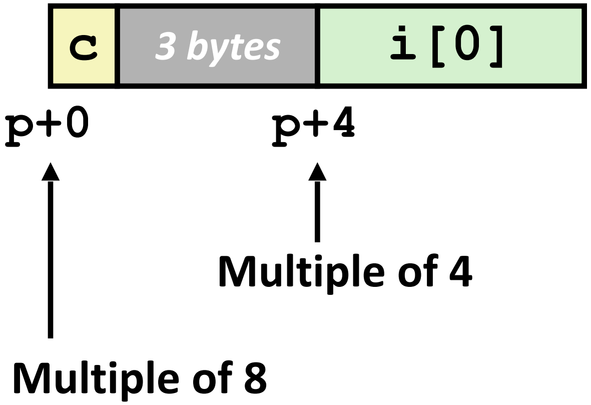

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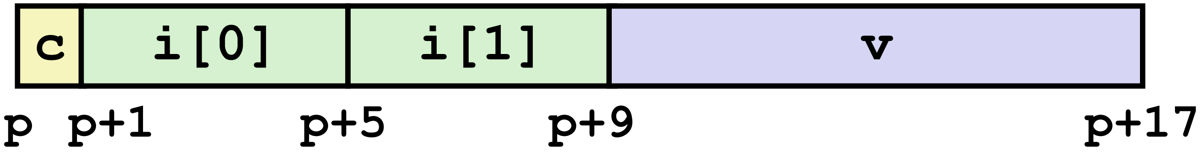

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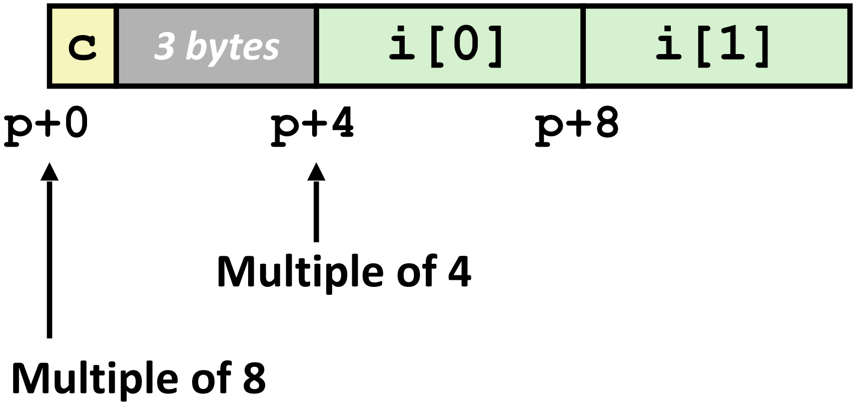

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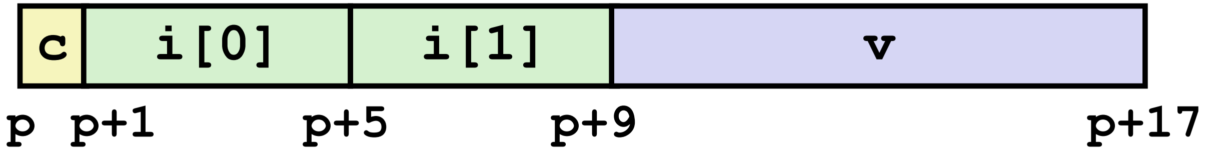

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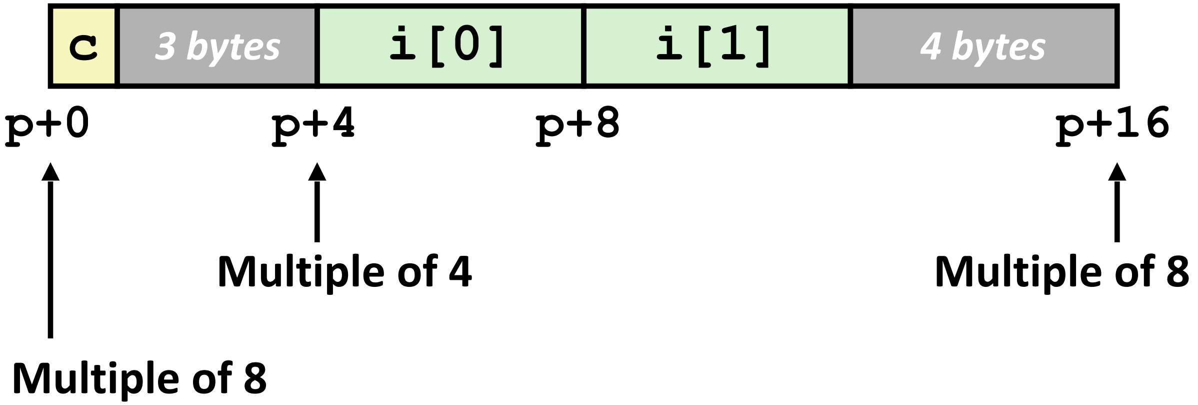

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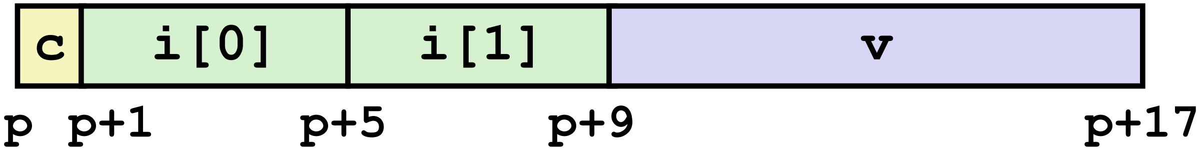

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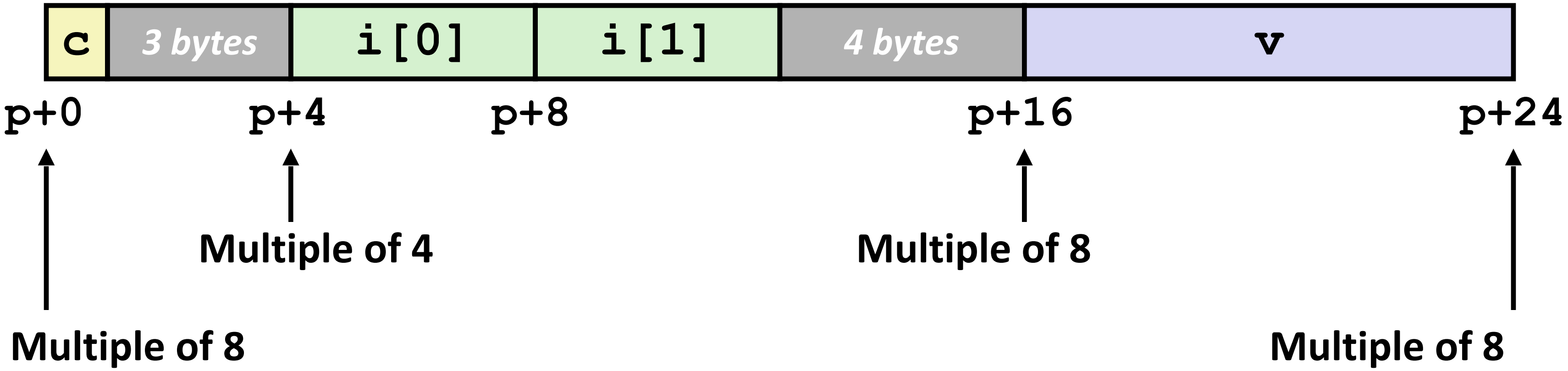

Alignment Principles

- Aligned Data
  - If the data type requires K bytes, address must be multiple of K
- Required on some machines; advised on x86-64
- Motivation for Aligning Data: Performance
  - Inefficient to load or store datum that spans quad word boundaries
  - Virtual memory trickier when datum spans 2 pages (later…)
  - Some machines don’t event support unaligned memory access
- Compiler
  - Inserts gaps in structure to ensure correct alignment of fields
  - `sizeof()` returns the actual size of structs (i.e., including padding)

Specific Cases of Alignment (x86-64)

- 1 byte: `char`, …
  - no restrictions on address
- 2 bytes: `short`, …
  - lowest 1 bit of address must be 0_2
- 4 bytes: `int`, `float`, …
  - lowest 2 bits of address must be 00_2
- 8 bytes: `double`, `long`, `char *`, …
  - lowest 3 bits of address must be 000_2

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- Within structure:
  - Must satisfy each element’s alignment requirement

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- Overall structure placement
  - Each structure has alignment requirement **K**
    - **K** = Largest alignment of any element
  - Initial address & structure length must be multiples of **K**
  - **WHY?!**

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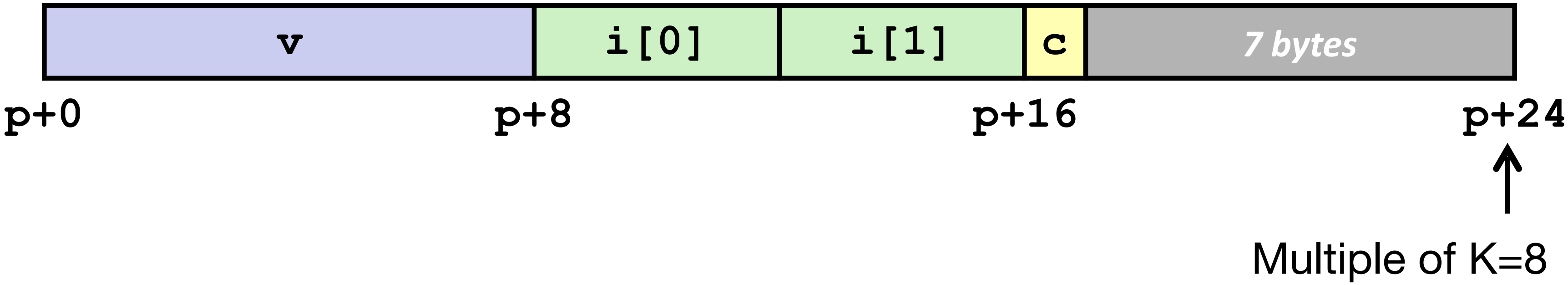
  - Initial address & structure length must be multiples of **K**
  - **WHY?!**

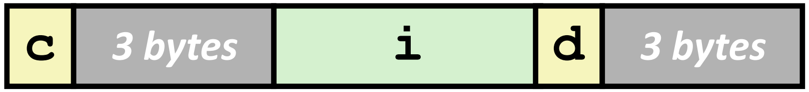
```
struct S2 {
  double v;
  int i[2];
  char c;
} *p;
```



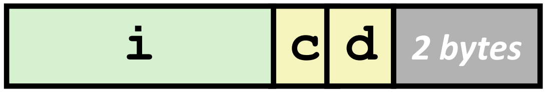
Saving Space

- Put large data types first in a Struct
- This is not something that a C compiler would do
  - But knowing low-level details empower a C programmer to write more efficient code

```
struct S4 {
  char c;
  int i;
  char d;
} *p;
```



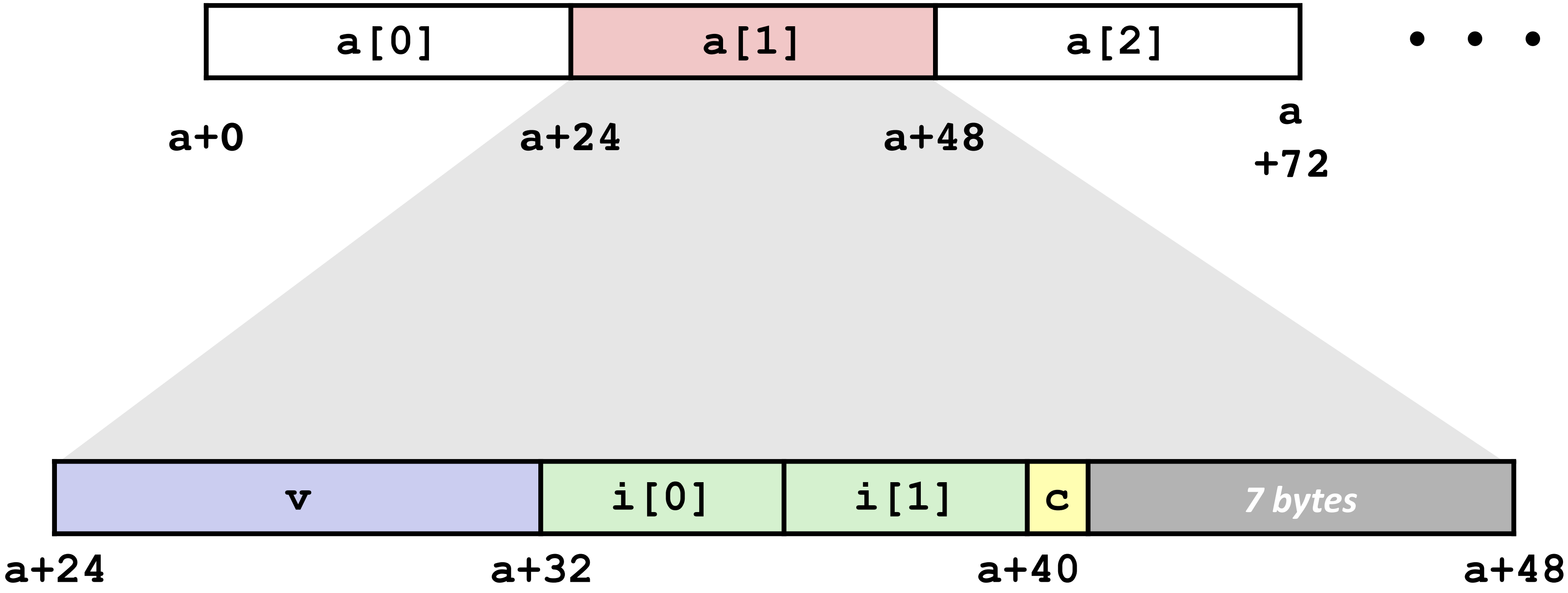
```
struct S5 {
  int i;
  char c;
  char d;
} *p;
```



Arrays of Structures

- Overall structure length multiple of K
- Satisfy alignment requirement for every element

```
struct S2 {
  double v;
  int i[2];
  char c;
} a[10];
```



Accessing Array Elements

```
struct S3 {
  short i;
  float v;
  short j;
} a[10];
```

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```
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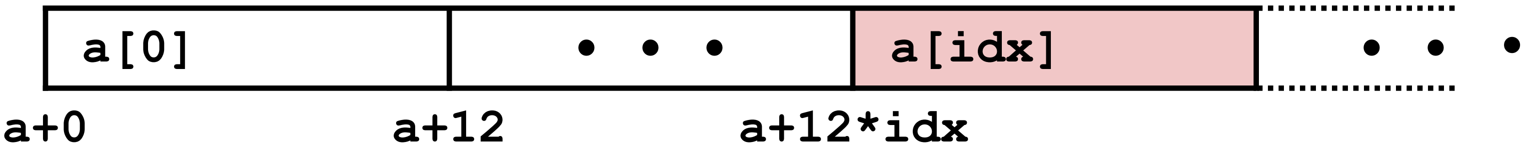

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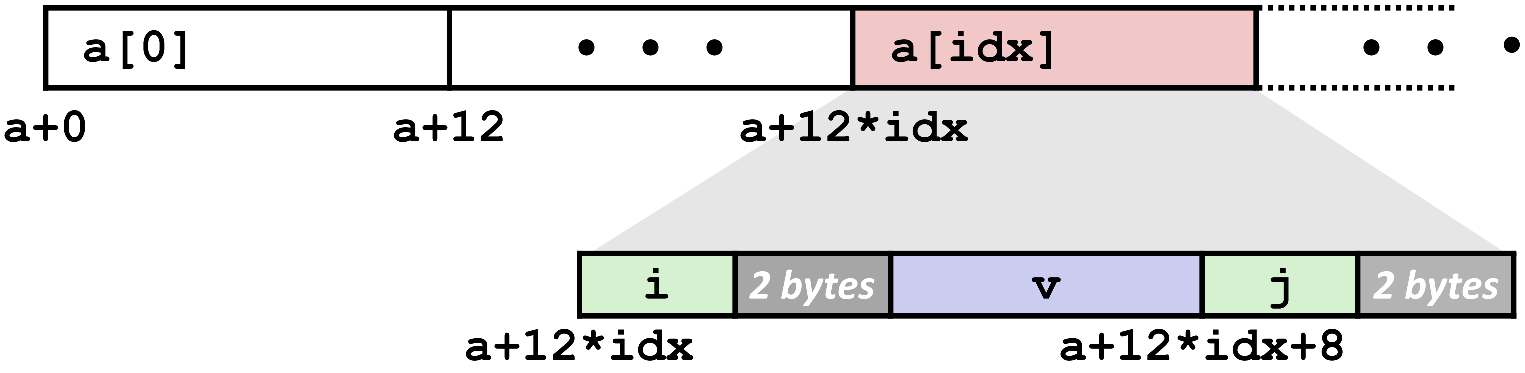

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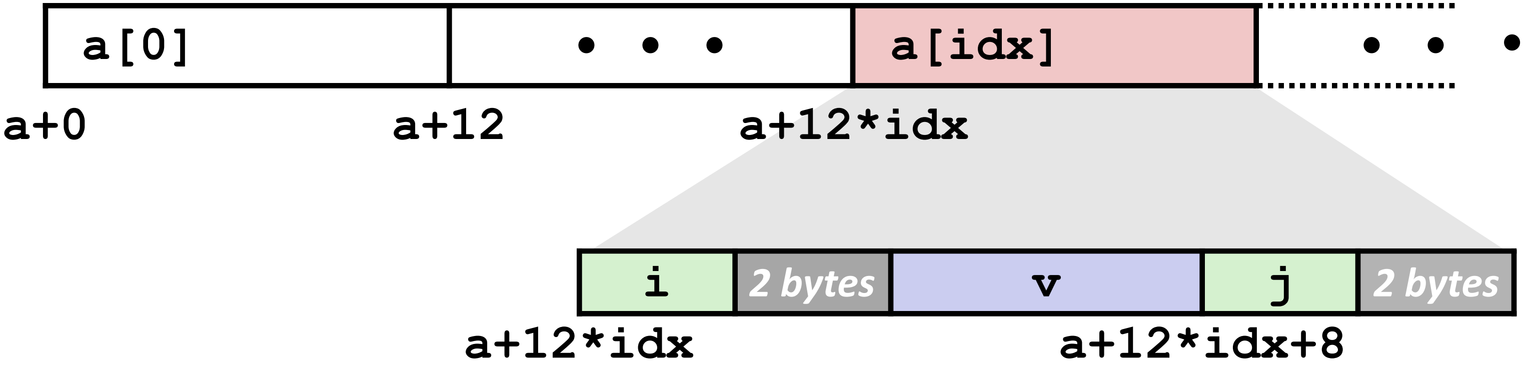
```
# %rdi = idx
leaq (%rdi,%rdi,2),%rax # 3*idx
movzwl a+8(,%rax,4),%eax
```



Today: Data Structures and Buffer Overflow

- Arrays
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Memory Referencing Bug Example

```
typedef struct {
  int a[2];
  double d;
} struct_t;

double fun(int i) {
  volatile struct_t s;
  s.d = 3.14;
  s.a[i] = 1073741824; /* Possibly out of bounds */
  return s.d;
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```
fun(0)   ➙     3.14
fun(1)   ➙     3.14
fun(2)   ➙     3.1399998664856
fun(3)   ➙     2.00000061035156
fun(4)   ➙     3.14
fun(6)   ➙     Segmentation fault
```

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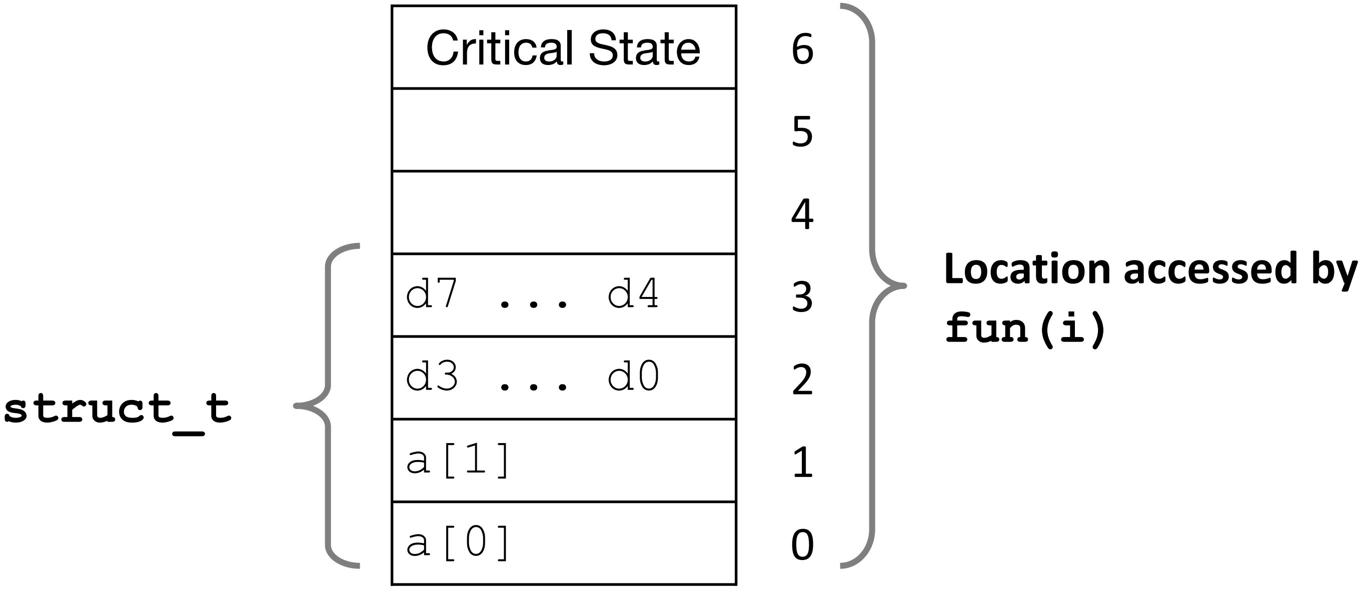

Critical State 6

5

4

d7 ... d4 3

d3 ... d0 2

a[1] 1

a[0] 0

struct_t

Location accessed by `fun(i)`

String Library Code

```
/* Get string from stdin */
char *gets(char *dest)
{
    int c = getchar();
    char *p = dest;
    while (c != EOF && c != '\n') {
        *p++ = c;
        c = getchar();
    }
    *p = '\0';
    return dest;
}
```

String Library Code

- Implementation of Unix function `gets()`
    - No way to specify limit on number of characters to read

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```

String Library Code

- Implementation of Unix function `gets()`
  - No way to specify limit on number of characters to read
- Similar problems with other library functions
  - **`strcpy`**, **`strcat`**: Copy strings of arbitrary length
  - **`scanf`**, **`fscanf`**, **`sscanf`**, when given **`%s`** conversion specification

```
/* Get string from stdin */
char *gets(char *dest)
{
    int c = getchar();
    char *p = dest;
    while (c != EOF && c != '\n') {
        *p++ = c;
        c = getchar();
    }
    *p = '\0';
    return dest;
}
```

Vulnerable Buffer Code

```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

```
void call_echo() {
    echo();
}
```

Vulnerable Buffer Code

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/* Echo Line */
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{
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    gets(buf);
    puts(buf);
}
```

```
void call_echo() {
    echo();
}
```

```
unix>./bufdemo-nsp
Type a string:01234567890123456789012
01234567890123456789012
```

Vulnerable Buffer Code

```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

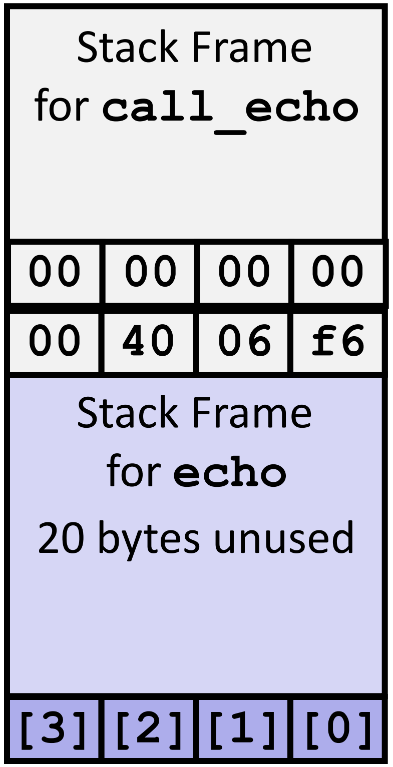
```
void call_echo() {
    echo();
}
```

```
unix>./bufdemo-nsp
Type a string:012345678901234567890123
012345678901234567890123
```

```
unix>./bufdemo-nsp
Type a string:0123456789012345678901234
Segmentation Fault
```

Buffer Overflow Stack Example

Before call to gets



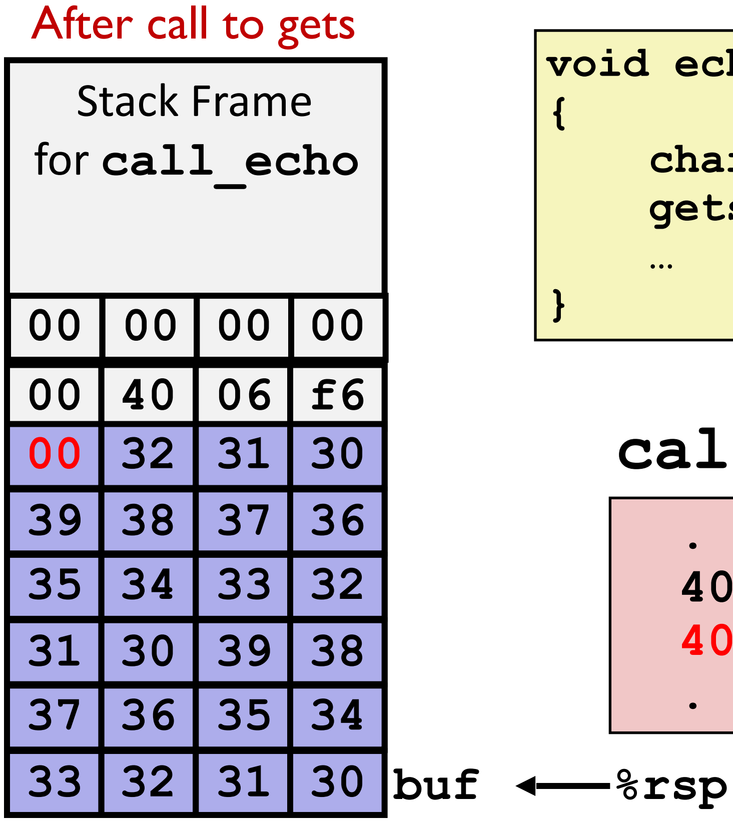
```
void echo()
{
      char buf[4];
      gets(buf);
      …
}
```

```
echo:
   subq  $24, %rsp
   movq  %rsp, %rdi
   call  gets
   …
```

call_echo:

```
   . . .
   4006f1:  callq   4006cf <echo>
   4006f6:  add     $0x8,%rsp
   . . .
```

Buffer Overflow Stack Example #1



After call to gets

Stack Frame
for `call_echo`

00	00	00	00
00	40	06	f6
00	32	31	30
39	38	37	36
35	34	33	32
31	30	39	38
37	36	35	34
33	32	31	30

buf ← %rsp

```
void echo()
{
    char buf[4];
    gets(buf);
    …
}
```

```
echo:
  subq   $24, %rsp
  movq   %rsp, %rdi
  call   gets
  …
```

call_echo:

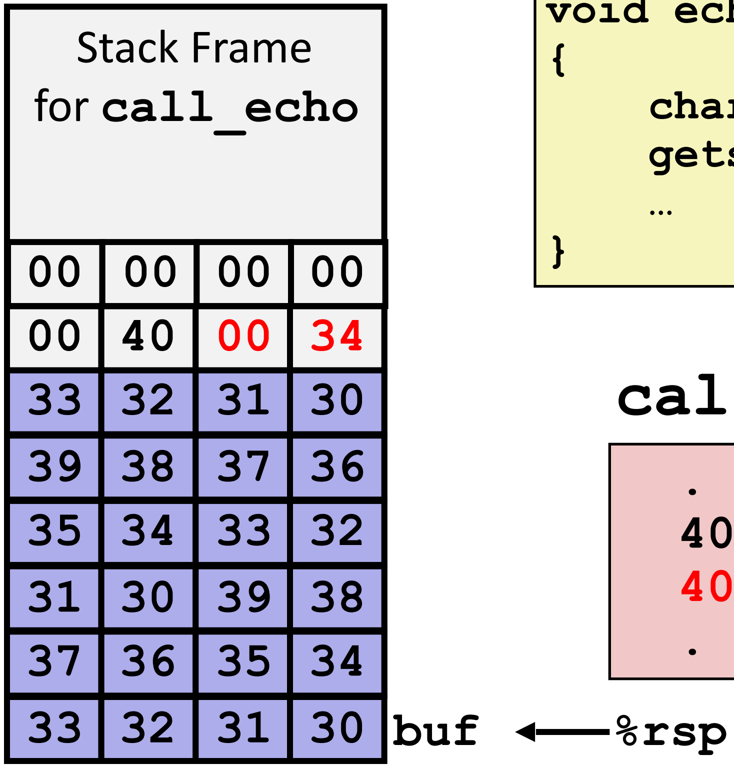
```
  . . .
  4006f1:   callq   4006cf <echo>
  4006f6:   add     $0x8,%rsp
  . . .
```

```
unix>./bufdemo-nsp
Type a string:01234567890123456789012
01234567890123456789012
```

Overflowed buffer, but did not corrupt state

Buffer Overflow Stack Example #2

After call to gets



Stack Frame for call_echo

00	00	00	00
00	40	00	34
33	32	31	30
39	38	37	36
35	34	33	32
31	30	39	38
37	36	35	34
33	32	31	30

buf ←%rsp

```
void echo()
{
    char buf[4];
    gets(buf);
    …
}
```

```
echo:
  subq  $24, %rsp
  movq  %rsp, %rdi
  call  gets
  …
```

call_echo:

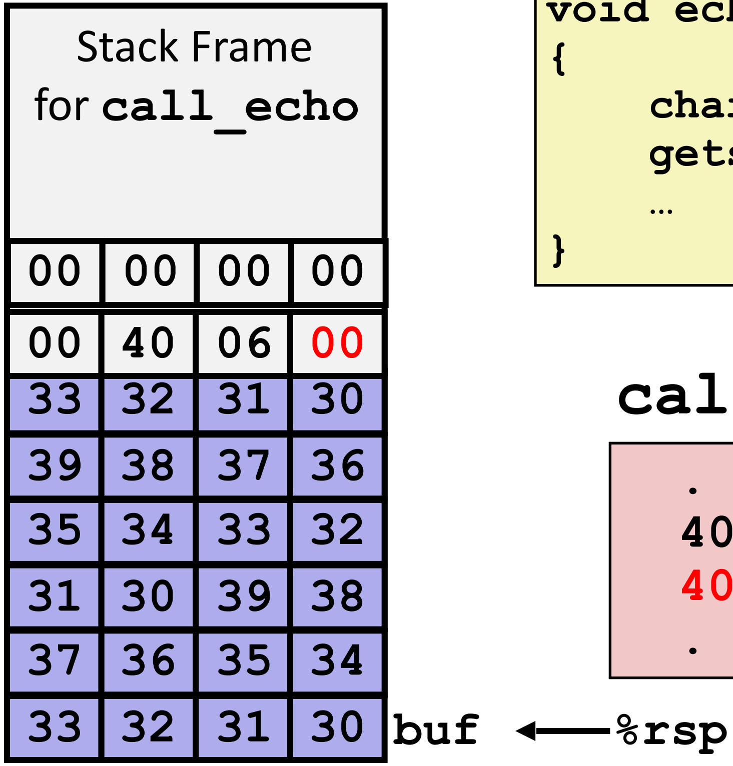
```
  . . .
  4006f1:  callq  4006cf <echo>
  4006f6:  add    $0x8,%rsp
  . . .
```

```
unix>./bufdemo-nsp
Type a string:0123456789012345678901234
Segmentation Fault
```

Overflowed buffer, and corrupt return address

Buffer Overflow Stack Example #3

After call to gets



Stack Frame for `call_echo`			
00	00	00	00
00	40	06	00
33	32	31	30
39	38	37	36
35	34	33	32
31	30	39	38
37	36	35	34
33	32	31	30

```
void echo()
{
    char buf[4];
    gets(buf);
    …
}
```

```
echo:
  subq  $24, %rsp
  movq  %rsp, %rdi
  call  gets
  …
```

`call_echo:`

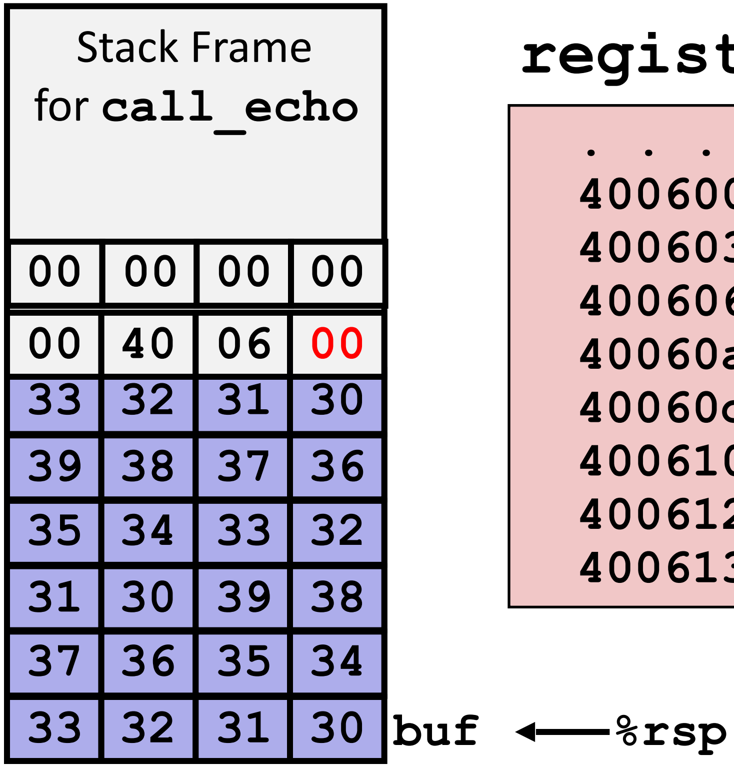
```
  . . .
  4006f1:  callq  4006cf <echo>
  4006f6:  add    $0x8,%rsp
  . . .
```

```
unix>./bufdemo-nsp
Type a string:01234567890123456789012
01234567890123456789012
```

Overflowed buffer, corrupt return address, but program appears to still work!

Buffer Overflow Stack Example #4

After call to gets



Stack Frame for `call_echo`

00	00	00	00
00	40	06	00
33	32	31	30
39	38	37	36
35	34	33	32
31	30	39	38
37	36	35	34
33	32	31	30

`register_tm_clones:`

```
 . . .
400600:  mov     %rsp,%rbp
400603:  mov     %rax,%rdx
400606:  shr     $0x3f,%rdx
40060a:  add     %rdx,%rax
40060d:  sar     %rax
400610:  jne     400614
400612:  pop     %rbp
400613:  retq
```

“Returns” to unrelated code

Could be code controlled by attackers!

Such problems are a BIG deal

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- Generally called a “buffer overflow”
  - when exceeding the memory size allocated for an array
  - It’s the #1 technical cause of security vulnerabilities
  - #1 overall cause is social engineering / user ignorance

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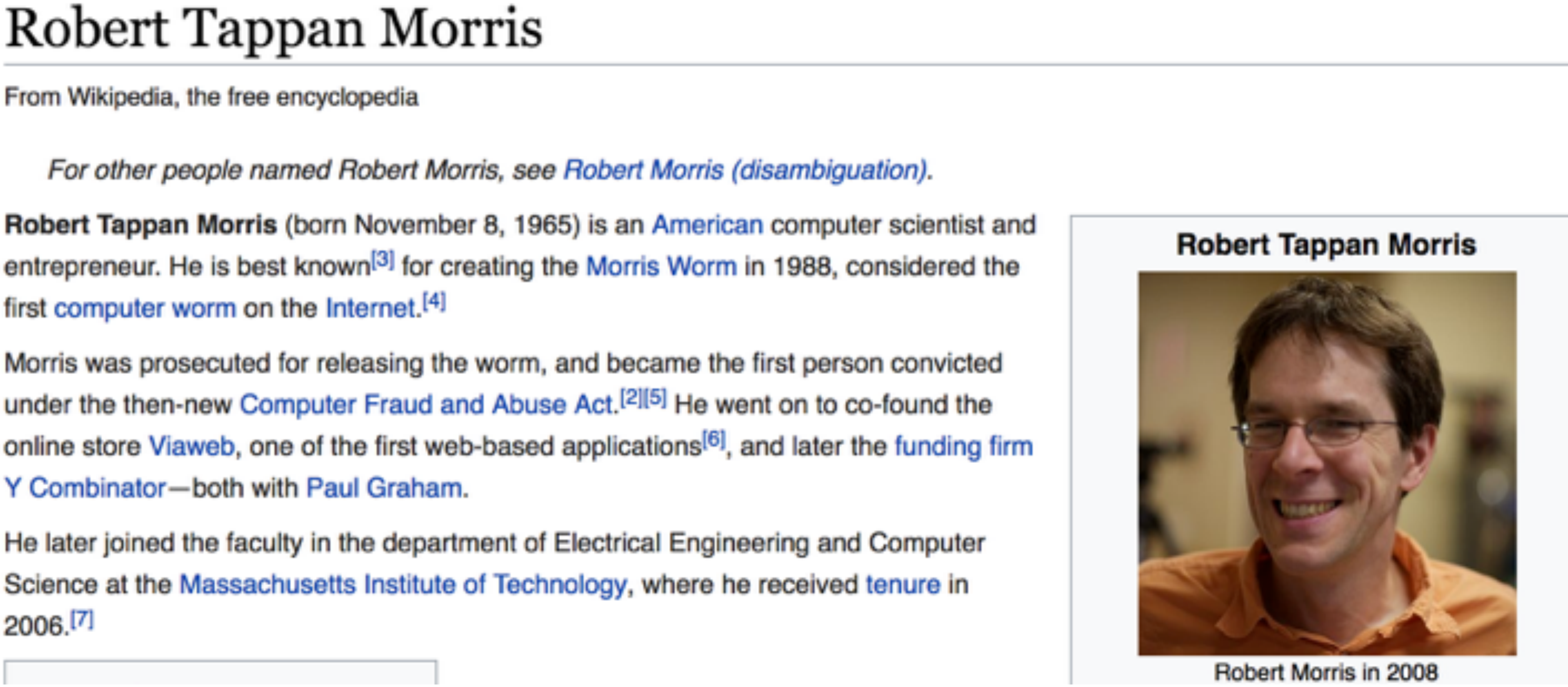
- Generally called a “buffer overflow”
  - when exceeding the memory size allocated for an array
  - It’s the #1 technical cause of security vulnerabilities
  - #1 overall cause is social engineering / user ignorance
- The original Internet worm (1988) exploits buffer overflow
  - Invaded 10% of the Internet
  - Robert Morris, the authors of the worm, was a graduate student at Cornell and was later prosecuted

Such problems are a BIG deal



Robert Tappan Morris

From Wikipedia, the free encyclopedia

For other people named Robert Morris, see Robert Morris (disambiguation).

Robert Tappan Morris (born November 8, 1965) is an American computer scientist and entrepreneur. He is best known[3] for creating the Morris Worm in 1988, considered the first computer worm on the Internet.[4]

Morris was prosecuted for releasing the worm, and became the first person convicted under the then-new Computer Fraud and Abuse Act.[2][5] He went on to co-found the online store Viaweb, one of the first web-based applications[6], and later the funding firm Y Combinator—both with Paul Graham.

He later joined the faculty in the department of Electrical Engineering and Computer Science at the Massachusetts Institute of Technology, where he received tenure in 2006.[7]

Robert Tappan Morris

Robert Morris in 2008

What to do about buffer overflow attacks

- Avoid overflow vulnerabilities
- Employ system-level protections
- Have compiler use “stack canaries”

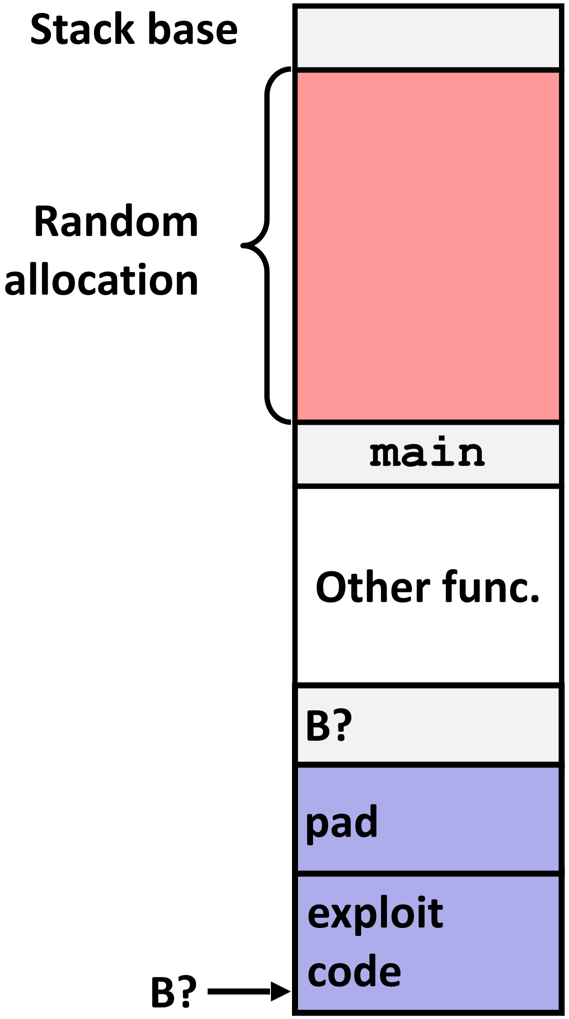
1. Avoid Overflow Vulnerabilities in Code (!)

```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    fgets(buf, 4, stdin);
    puts(buf);
}
```

- For example, use library routines that limit string lengths
  - `fgets` instead of `gets`
  - `strncpy` instead of `strcpy`
  - Don’t use `scanf` with `%s` conversion specification
    - Use `fgets` to read the string
    - Or use `%ns` where `n` is a suitable integer

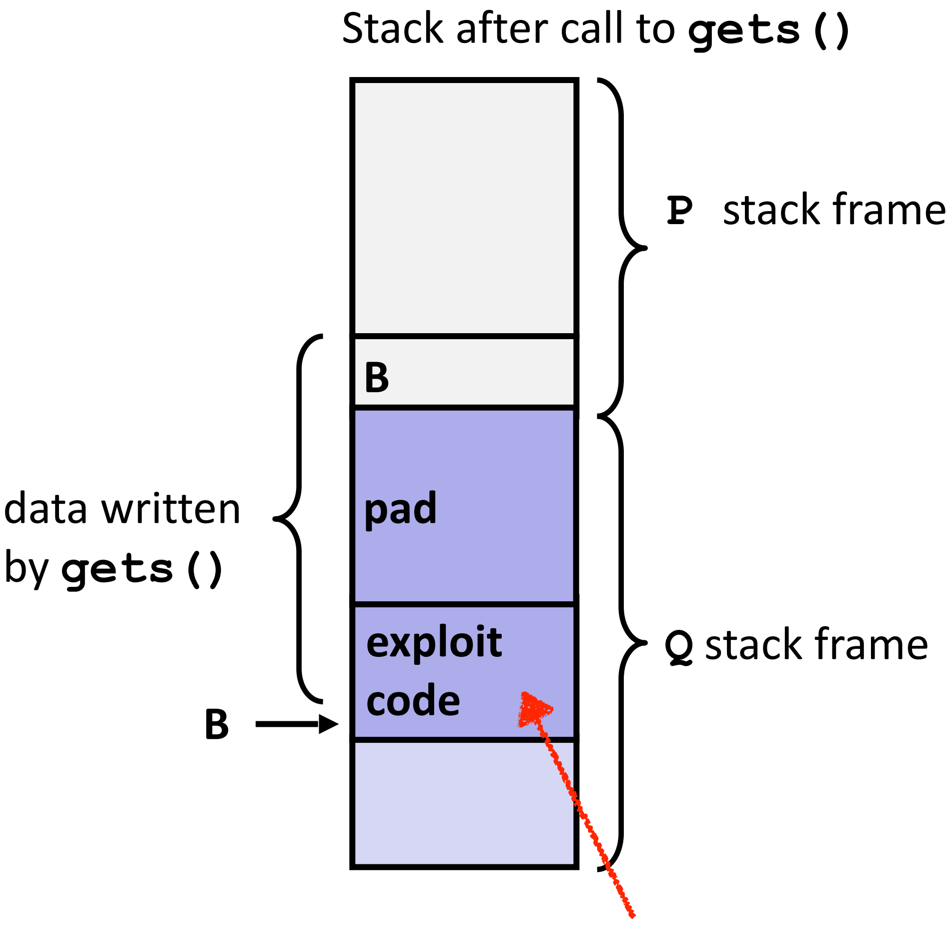
2. System-Level Protections can help

- Randomized stack offsets
  - At start of program, allocate random amount of space on stack
  - Shifts stack addresses for entire program
  - Makes it difficult for hacker to predict beginning of inserted code



2. System-Level Protections can help

- Nonexecutable code segments
  - In traditional x86, can mark region of memory as either “read-only” or “writeable”
  - Can execute anything readable
  - X86-64 added explicit “execute” permission
  - Stack marked as non-executable



Any attempt to execute this code will fail

3. Stack Canaries can help

- Idea
    - Place special value (“canary”) on stack just beyond buffer
    - Check for corruption before exiting function
- GCC Implementation
    - `-fstack-protector`
    - Now the default (disabled earlier)

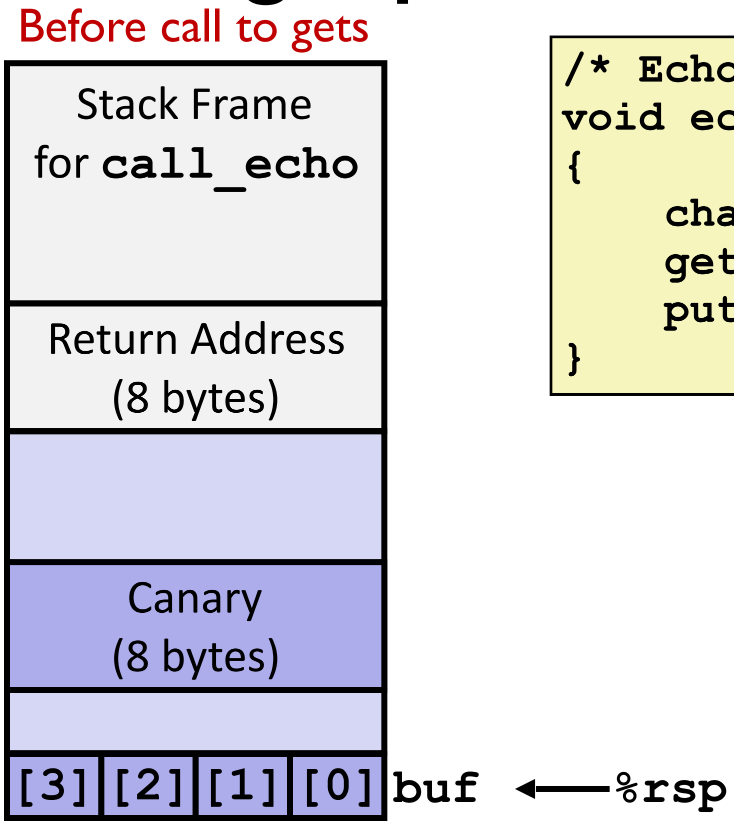
3. Stack Canaries can help

- Idea
  - Place special value (“canary”) on stack just beyond buffer
  - Check for corruption before exiting function
- GCC Implementation
  - `-fstack-protector`
  - Now the default (disabled earlier)

```
unix>./bufdemo-sp
Type a string:0123456
0123456
```

```
unix>./bufdemo-sp
Type a string:01234567
*** stack smashing detected ***
```

Setting Up Canary

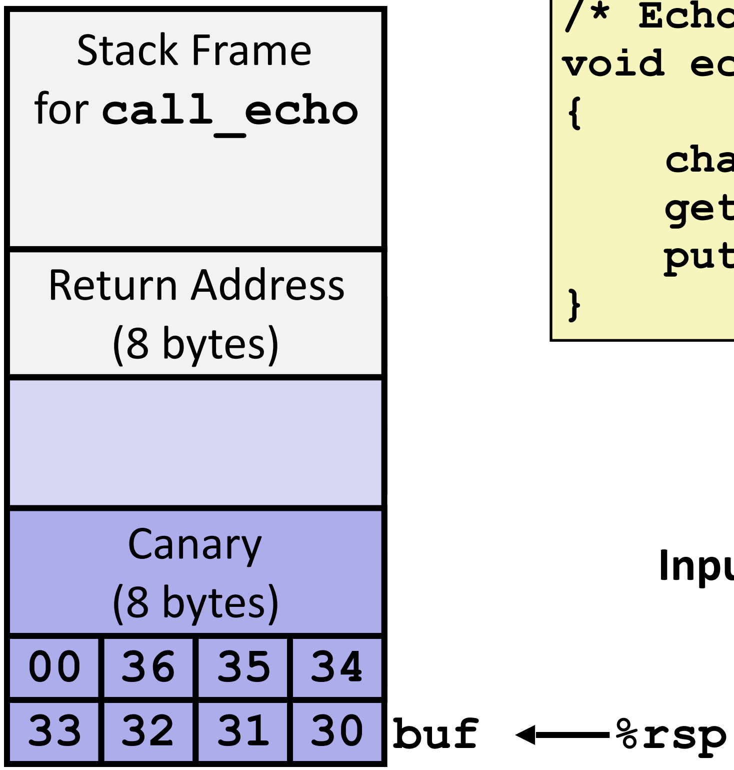


```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

```
echo:
    . . .
    movq    %fs:40, %rax  # Get canary
    movq    %rax, 8(%rsp) # Place on stack
    xorl    %eax, %eax    # Erase canary
    . . .
```

Checking Canary

After call to gets



```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

Input: ***0123456***

```
echo:
    . . .
    movq    8(%rsp), %rax       # Retrieve from stack
    xorq    %fs:40, %rax        # Compare to canary
    je      .L6                 # If same, OK
    call    __stack_chk_fail    # FAIL
.L6:        . . .
```